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Acceleressence: Dark Energy from a Phase Transition at the Seesaw Scale

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Abstract

Simple models are constructed for "acceleressence" dark energy: the latent heat of a phase transition occurring in a hidden sector governed by the seesaw mass scale $v^2/M_{\rm Pl}$, where v is the electroweak scale and $M_{\rm Pl}$ the gravitational mass scale. In our models, the seesaw scale is stabilized by supersymmetry, implying that the LHC must discover superpartners with a spectrum that reflects a low scale of fundamental supersymmetry breaking. Newtonian gravity may be modified by effects arising from the exchange of fields in the acceleressence sector whose Compton wavelengths are typically of order the millimeter scale. There are two classes of models. In the first class the universe is presently in a metastable vacuum and will continue to inflate until tunneling processes eventually induce a first order transition. In the simplest such model, the range of the new force is bounded to be larger than 25 μm in the absence of fine-tuning of parameters, and for couplings of order unity it is expected to be $\approx$ 100 μm. In the second class of models thermal effects maintain the present vacuum energy of the universe, but on further cooling, the universe will "soon" smoothly relax to a matter dominated era. In this case, the range of the new force is also expected to be of order the millimeter scale or larger, although its strength is uncertain. A firm prediction of this class of models is the existence of additional energy density in radiation at the eV era, which can potentially be probed in precision measurements of the cosmic microwave background. An interesting possibility is that the transition towards a matter dominated era has occurred in the very recent past, with the consequence that the universe is currently decelerating.

1 Dark Energy from a Phase Transition

Cosmological observations of Type Ia supernovae, the cosmic microwave background radiation and large scale structure provide strong evidence that the universe is flat and composed of about 70% dark energy and 30% dark matter [1, 2, 3]. The dark energy, which is driving a recent acceleration in the expansion in the universe, has negative pressure and cannot be interpreted as matter or radiation. Rather, this unusual fluid may be some form of vacuum energy, with an energy density of order $(10^{-3}\text{ eV})^4$. A crucial question is whether this vacuum energy is time independent – a "hard" cosmological constant, Λ – or evolves with time – a "soft" vacuum energy. An example of the latter is "quintessence", a scalar field energy that evolves slowly over many decades of expansion of the universe [4]. However, theories of quintessence involve an unnaturally small mass scale of order the Hubble parameter, 10^{-33} eV, and do not explain why this field energy is just dominating the universe in the present epoch. A hard cosmological constant also suffers from this "Why now?" problem; are we really witnessing the transition to an era of eternal inflation?

Our present understanding of the hot big bang is one of a succession of phase transitions interspersed with eras of smooth cooling. The phase transitions are the cosmological manifestation of symmetry breaking, as the underlying vacuum shifts from one stable minimum to another. Given the standard model of particle physics, it is extremely plausible that phase transitions occurred both as the temperature cooled through the electroweak scale, v, and through the scale of strong interactions, $\Lambda_{\rm QCD}$. At higher temperatures there may well have been other phase transitions associated, for example, with the breaking of lepton number (to generate right-handed neutrino masses and for leptogenesis), the breaking of grand unified gauge symmetries, and the generation of an early era of cosmic inflation. At each of these phase transitions it is likely that the universe was dominated for a period by the vacuum energy, or latent heat, of the associated change in vacuum state. It therefore seems plausible to us that the present cosmic expansion is fueled by the soft vacuum energy of some phase transition associated with an energy scale of 10^{-3} eV. We label this phenomenon acceleressence.

At first sight it does not seem reasonable that there could be a phase transition in the universe with a vacuum energy of order $(10^{-3}\text{ eV})^4$, because we have not discovered any particle physics symmetry breaking at the 10^{-3} eV scale. However, at low energies we know that interactions between particles can get very small, suppressed by inverse powers of a large mass scale, so that this new particle physics may be decoupled from us. For example, all interactions of the neutrino decouple at low energies, and its mass is often assumed to arise from inverse powers of the large right-handed neutrino mass M_R, $m_\nu \simeq v^2/M_R$. Suppose that acceleressence occurs in some hidden sector that interacts with the standard model only by gravity. It could be that the mass

scale of this sector is also generated by a seesaw mechanism, taking the value $v^2/M_{\rm Pl} \simeq 10^{-3}$ eV, where the Planck mass, $M_{\rm Pl}$, is the scale of gravity. It is intriguing that this ratio of known scales gives the observed energy scale of dark energy. If such a sector underwent a phase transition it could cause cosmic acceleration, naturally explaining the "Why now?" problem [5]. In this paper we aim to construct the simplest models of such a hidden phase transition.

If there is to be a new scale of particle physics at $v^2/M_{\rm Pl} \simeq 10^{-3}$ eV, how can it be made stable to radiative corrections? This appears even more daunting than the usual hierarchy problem of making v stable to radiative corrections. Remarkably supersymmetry can do both. The usual hierarchy problem is solved by requiring that the scale of supersymmetry breaking in the standard model sector is of order the electroweak scale: $\tilde{m} \simeq v$. If this is the only breaking of supersymmetry in nature, and if the acceleressence sector only couples gravitationally to this supersymmetry breaking, then the scale of supersymmetry breaking in the acceleressence sector will naturally be

$$m_D \simeq \frac{\tilde{m}^2}{M_{\rm Pl}} \simeq \frac{v^2}{M_{\rm Pl}} \simeq 10^{-3} \text{ eV}, \tag{1}$$

and is stable to radiative corrections.

Our task in this letter is to build the simplest models of acceleressence and study their consequences. In general these theories possess a sector involving a scalar field ϕ, the acceleressence field, such that all the supersymmetry breaking mass parameters in its potential are of order m_D. We assume that the cosmological constant vanishes in the true minimum of the zero temperature potential. Before the phase transition associated with dark energy has occurred, $\langle \phi \rangle = 0$. Clearly the crucial question is the behavior of the field near the origin. In our first model, ϕ has a positive mass squared and we live in a false vacuum, with the phase transition induced by a trilinear ϕ^3 interaction. The tunneling rate to the true minimum may be very slow, so that the universe may enter a prolonged era of inflation before undergoing a first order phase transition. In the second model, ϕ has a negative mass squared so that there is no local minimum of the potential at the origin. Nevertheless, thermal corrections to the effective potential are sufficient to maintain $\langle \phi \rangle = 0$ today. This thermal barrier will rapidly disappear as the universe cools, and hence a phase transition towards a matter dominated era is imminent. An interesting possibility is that this transition has already occurred, albeit in the very recent past. In this case the universe is currently decelerating, leading to observable consequences for future precision measurements of the distance-redshift relation.

There are alternative ideas for understanding the size of the dark energy density. It may be related to the neutrino energy density [6] in such a way that the dark energy resides in a slowly evolving scalar field. In axion models, the dark energy may be false vacuum energy associated with the size of explicit $U(1)_{\rm PQ}$ breaking coming from higher dimension operators [7]. Alternatively, in theories with extra spatial dimensions, the smallness of the dark energy density

may follow from an exponential wavefunction profile in the bulk [8].

2 Models of Acceleressence

Our models have the following basic structure. We have a sector that contains a scalar field ϕ, the acceleressence field, responsible for the dark energy. This acceleressence sector interacts with the other sectors only through gravitationally suppressed interactions. In particular, once supersymmetry is broken at the TeV scale in the standard model sector, its effects are transmitted to the acceleressence sector through the following operators:

$$\int d^4\theta \, \frac{X^\dagger X}{{M_{\rm Pl}}^2} \Phi^\dagger \Phi, \qquad \int d^4\theta \, \frac{X + X^\dagger}{M_{\rm Pl}} \Phi^\dagger \Phi, \tag{2}$$

where Φ is a chiral superfield containing ϕ as the lowest component, and X is a superfield that breaks supersymmetry so that $F_X \simeq (\mathrm{TeV})^2$. This generates a soft supersymmetry-breaking mass and trilinear interaction for ϕ of order $F_X/M_{\rm Pl} \equiv m_D \simeq 10^{-3}$ eV, which eventually produces dark energy of the observed size. In theories where tree-level couplings between Φ and X are absent, the operators in Eq. (2) are generated effectively at loop level so that the scale of the fundamental supersymmetry breaking can be $F_X \simeq (10\!\sim\!100~\mathrm{TeV})^2$.

2.1 Acceleressence from a false vacuum

We now present the simplest model realizing our scenario. The acceleressence sector consists of a single chiral superfield Φ with the superpotential

$$W = \frac{\lambda}{3} \Phi^3. \tag{3}$$

Taking supersymmetry breaking effects into account, the scalar potential is given by

$$V = \lambda^2 |\phi|^4 - (A \phi^3 + {\rm h.c.}) + m^2 |\phi|^2 + V_0, \tag{4}$$

where, without loss of generality, λ and A can be taken real and positive by rotating phases of fields. Here, m and A are supersymmetry breaking parameters of order m_D, and V_0 is a constant determined by the condition that the cosmological constant is vanishing at the true minimum of the potential.

We assume that m^2 is positive so that the model has a (local) minimum at the origin in field space. If A is sufficiently large, $9A^2 > 8\lambda^2 m^2$, the model has a second minimum at $\langle\phi\rangle \neq 0$. This second minimum has a lower energy than the minimum at the origin if

$$A > \lambda\, m. \tag{5}$$

We require this condition to be satisfied, so that the minimum at $\langle\phi\rangle = 0$ is only a local minimum. Then, for A sufficiently larger than λm, we find

$$V_0 \simeq \frac{27A^4}{16\lambda^6} = O\Big(\frac{A^4}{\lambda^6}\Big). \tag{6}$$

This is the vacuum energy density we observe today, if the ϕ field is trapped in the local minimum at the origin. The trapping at the origin naturally occurs because it is likely that the universe starts at $\langle\phi\rangle = 0$ due to thermal effects or an induced ϕ mass term during inflation. The lifetime for the decay of this metastable vacuum can easily be made longer than the age of the universe. We then obtain the observed magnitude of the dark energy for natural values of parameters, $\lambda \simeq 1$ and $A \simeq 10^{-3}$ eV.

2.2 Acceleressence from a thermal vacuum

In the model discussed above, the mass squared for the acceleressence field ϕ was assumed to be positive. We can also consider a model in which the acceleressence field has a negative mass squared, but is trapped at the origin by thermal effects. Building such a model, however, is not entirely trivial due to the potential conflict between the observed size of the dark energy and the constraint from big-bang nucleosynthesis on the thermal energy density of the acceleressence sector. For example, we cannot simply take the model of section 2.1 and make m^2 negative, as the resulting model does not have a viable parameter region explaining the observed dark energy while satisfying all phenomenological constraints. In this section we present a realistic model with the acceleressence field having a negative mass squared at the origin.

We take our acceleressence sector to be a supersymmetric $U(1)$ gauge theory with three chiral superfields $\Phi(+1)$, $\bar{\Phi}(-1)$ and $S(0)$, where the numbers in parentheses represent the $U(1)$ charges. The superpotential of the model is

$$W = \lambda S \Phi \bar{\Phi}, \tag{7}$$

where λ is a coupling constant. Now, suppose that Φ and $\bar{\Phi}$ obtain negative squared masses, $-m_\phi^2$ and $-m_{\bar{\phi}}^2$, and S obtains a positive squared mass, m_s^2, from supersymmetry breaking (where $m_\phi^2, m_{\bar{\phi}}^2, m_s^2 > 0$ are of order m_D^2). The scalar potential is given by

$$\begin{aligned} V &= |\lambda\phi\bar{\phi}|^2 + |\lambda s\phi|^2 + |\lambda s\bar{\phi}|^2 + \frac{g^2}{2}(|\phi|^2 - |\bar{\phi}|^2)^2 \\ &\quad + m_s^2|s|^2 - m_\phi^2|\phi|^2 - m_{\bar{\phi}}^2|\bar{\phi}|^2 + V_0, \end{aligned} \tag{8}$$

where g is the $U(1)$ gauge coupling and V_0 is a constant to be chosen to make the cosmological constant vanishing at the true minimum of the potential. Note that in addition to the gauge

symmetry, this theory possesses a global $U(1)$ symmetry under which ϕ and $\bar{\phi}$ have the same charge. Here we have assumed the absence of scalar trilinear interactions for simplicity.

For a somewhat suppressed superpotential coupling $\lambda^2 \ll g^2$, the minimum of the potential Eq. (8) lies at $\langle s \rangle = 0$ and $\langle \phi \rangle^2 \simeq \langle \bar{\phi} \rangle^2 \simeq (m_\phi^2 + m_{\bar{\phi}}^2)/2\lambda^2$. At this point in field space both the gauge and the global symmetries are broken, so the spectrum contains a massless Goldstone boson. Requiring $V = 0$ at the minimum, we obtain

$$V_0 \simeq \frac{(m_\phi^2 + m_{\bar{\phi}}^2)^2}{4\lambda^2}. \tag{9}$$

The potential Eq. (8) with Eq. (9) does not support a constant vacuum energy, as there is no local minimum in the potential. The situation, however, can be different if this sector has a finite temperature $T \neq 0$. In this case the effective potential receives an additional contribution, which is given at high temperature by

$$\delta V \simeq \frac{\lambda^2}{4} T^2 |s|^2 + \frac{g^2}{2} T^2 (|\phi|^2 + |\bar{\phi}|^2), \tag{10}$$

for $\lambda^2 \ll g^2$. Therefore, as long as $g^2 T^2/2 \gtrsim m_\phi^2$ and $m_{\bar{\phi}}^2$, the fields are thermally trapped to $\langle s \rangle = \langle \phi \rangle = \langle \bar{\phi} \rangle = 0$ and the vacuum energy is given by V_0 in Eq. (9). This leads to the accelerated expansion of our universe as long as the thermal energy density is smaller than the vacuum energy density, which is actually the case as we will see below.

In general, models of acceleressence using thermal effects are subject to severe phenomenological constraints. The success of big-bang nucleosynthesis constrains the radiation energy density in the acceleressence sector, ρ_ϕ, to be much smaller than that in photons, ρ_γ. We here parameterize this constraint as $\rho_\phi \lesssim \epsilon\, \rho_\gamma$, where $\epsilon \simeq 0.1$. Since $\rho_\phi \simeq (\pi^2/30) g_\phi T^4$ and $\rho_\gamma \simeq (\pi^2/15) T_\gamma^4$, the constraint can be written as

$$T^4 \lesssim \frac{2\epsilon}{g_\phi} T_\gamma^4, \tag{11}$$

where g_ϕ is the number of effective degrees of freedom in the acceleressence sector and T_γ is the photon temperature. In the present model, $g_\phi = 15$. The temperature of the acceleressence sector must also satisfy the condition such that it traps the fields in a local minimum. In the present model, this condition is given by

$$\frac{g^2}{2} T^2 \gtrsim m_\phi^2,\, m_{\bar{\phi}}^2. \tag{12}$$

Using Eqs. (11, 12) in Eq. (9) we then find that the parameters of the model must satisfy

$$\frac{\lambda}{g^2} \lesssim \left(\frac{\epsilon}{30} \frac{T_\gamma^4}{V_0} \right)^{\frac{1}{2}} \simeq 10^{-3}, \tag{13}$$

where we have used $V_0 \simeq 3 \times 10^{-11}$ eV^4 and $T_\gamma \simeq 2.4 \times 10^{-4}$ eV. Assuming $g = O(1)$, this requires a somewhat small coupling of $\lambda \lesssim 10^{-3}$. The small value of the quartic coupling for the acceleressence field is protected against radiative corrections by imposing an approximate $U(1)_R$ symmetry on the acceleressence sector that forbids a $U(1)$ gaugino mass. Note that with the condition Eq. (11) satisfied, the radiation energy density in the acceleressence sector, ρ_ϕ, is much smaller than the vacuum energy density, V_0, so that the accelerated expansion of the universe necessarily follows.

What is the future of the universe in such a scenario? At some point the temperature in the acceleressence sector falls to a point where the inequality Eq. (12) is no longer satisfied. The field of higher m^2 then start evolving at the Hubble rate, tracking the minimum of its thermal effective potential. However, during this era the vacuum energy only changes by a negligible amount so that w is still essentially -1. This era ends when the field reaches some critical value. At this point thermal effects in the potential disappear, and both ϕ and $\bar{\phi}$ fields rapidly acquire large values and oscillate about the minimum of the potential. The vacuum energy is then essentially instantly converted first into matter and then into the radiation energy of Goldstone bosons in the acceleressence sector. This makes the ultimate future of the universe to be dominated by cold dark matter. An intriguing possibility is that the conversion of dark energy to radiation energy described above has already occurred, albeit in the very recent past, with the deceleration parameter jumping from ≈ -0.5 to $\approx +0.8$, so that the universe is currently decelerating. The present value of the deceleration parameter may vary as the model is changed and typically lies between $\approx +0.5$ and $\approx +0.8$ in simple models. This leads to observable consequences for the very recent expansion of the universe, which may be probed by future observations of the distance-redshift relation.

2.3 Origin of supersymmetry breaking

In the models discussed above, the scale of the fundamental supersymmetry breaking should be low, $F_X \simeq (1 \sim 100 \text{ TeV})^2$, to have $m_D \simeq 10^{-3}$ eV. Here we discuss some explicit examples for such theories. The first example we discuss is a class of theories where supersymmetry is dynamically broken at around a TeV by nearly conformal gauge interactions. These theories have a dual 5D description in which supersymmetry is broken on the infrared (TeV) brane in a warped extra dimension [9, 10]. The standard-model gauge fields propagate in the bulk and matter fields are located on the ultraviolet (Planck) brane. Now, suppose we introduce a Φ superfield on the Planck brane with the superpotential of Eq. (3). Supersymmetry breaking on the TeV brane then produces the soft supersymmetry breaking parameters for ϕ through anomaly mediation [11]: $m^2 = 4\lambda^4 M^2$ and $A = 2\lambda^3 M$, where $M = m_{3/2}/16\pi^2$ with $m_{3/2}$ the gravitino mass. The soft mass squared m^2 also receives contribution from the possible terms

on the Planck brane: $\int d^4\theta\, H^\dagger H \Phi^\dagger \Phi / M_{\rm Pl}^2$ if the Higgs fields are localized towards the Planck brane ($c_H > 1/2$), or $\int d^2\theta\, (\Phi/M_{\rm Pl}) W^\alpha W_\alpha$ via a finite sum of one-loop diagrams involving the standard-model gauge bosons and their superpartners. In this class of models $m_{3/2}$ can naturally be in the 10 TeV region [10], so that the desired values for m^2 and A (satisfying Eq. (5)) can be generated in certain parameter regions. This then gives the correct amount of dark energy with $\lambda = O(0.1 \sim 1)$.

Another example is based on the gauge mediation scenario [12], but with the messenger and standard-model matter fields geometrically separated by extra spatial dimensions, for example by a flat extra dimension having the size around the grand unification scale. The standard-model gauge fields located in the bulk then transmit supersymmetry breaking from the messenger sector to the standard model sector. The size of supersymmetry breaking in the messenger sector can be of order $10 \sim 100$ TeV. If this is the largest supersymmetry breaking in the model, the Φ field located on the standard-model brane receives soft supersymmetry-breaking parameters m^2 and A with the appropriate size through anomaly mediation and operators located on that brane, as in the models in the previous paragraph. This type of model also provides an explicit example of our scenario.

In both examples of supersymmetry breaking given above, the spatial separation of Φ from the supersymmetry breaking field F_X implies that ϕ does not feel supersymmetry breaking from tree-level supergravity mediation; rather the dominant contribution arises at one loop from anomaly mediation. This leads to $m \simeq 10^{-4}\lambda^2(\sqrt{F_X}/10~\text{TeV})$ eV, easily allowing F_X to be in the range of $10 \sim 100$ TeV. These low values of F_X imply a rather light gravitino mass of $0.01 \sim 1$ eV, so that the lightest supersymmetric particle cannot be weakly interacting cold dark matter. The dark matter in our theories should be provided by a generic particle with TeV-sized mass and cross section. Such a particle may arise from fields localized on the infrared brane in warped models.

3 Potential Signatures

Here we discuss some potential signatures of our models. In our scenario, fields in the acceleressence sector may interact with the standard model fields through Planck-suppressed operators. Suppose that the Φ field in the model of section 2.1 interacts with the standard-model gauge fields through the following operator:

$$\int d^2\theta\, \frac{\Phi}{M_{\rm Pl}} {\rm Tr}\,[W^\alpha W_\alpha] \rightarrow \frac{\phi}{M_{\rm Pl}} {\rm Tr}\,[F^{\mu\nu} F_{\mu\nu}]\,, \qquad (14)$$

where W_α represents the field-strength superfields for the standard-model gauge fields. This induces a modification of the gravitational potential between two bodies of masses m_1 and m_2

separated at a distance r through the ϕ exchange: $V_{\rm grav} = -(1+\alpha e^{-r/l})G_N m_1 m_2/r$. The size of the modification, α, depends on an unknown coefficient of the operator in Eq. (14); we naturally expect that it is of order unity, but it could be small. The range of modification, l, is determined by the mass of the ϕ scalar: $l \simeq m^{-1}$. An interesting aspect of the model is that the size of the dark energy has an implication for the range of the modification l. To see this we can explicitly minimize the potential of Eq. (4) and write V_0 as

$$V_0 = \frac{m^4}{\lambda^2} f\left(\frac{\lambda m}{A}\right), \tag{15}$$

where f is a function defined by $f(x) = (27 - 36x^2 + 8x^4 + (9 - 8x^2)^{3/2})/32x^4$. The function $f(x)$ has the property that for $x < 0.8$, $f(x) > 1$. Therefore, for a parameter region $\lambda m/A \lesssim 0.8$ we obtain a lower bound on $l \simeq m^{-1}$:

$$l \gtrsim \frac{1}{\sqrt{\lambda}} V_0^{-\frac{1}{4}}. \tag{16}$$

For the vacuum at $\phi = 0$ to be metastable, $\lambda m/A < 1$ (see Eq. (5)), so that this bound on l applies to most of the parameter space of the model. (The exception is when A is very close to λm.)

A numerical bound on the range l is obtained from the upper bound on the coupling λ: $\lambda \lesssim 4\pi$. Using $V_0 \simeq 3 \times 10^{-11}$ eV^4, we obtain $l \gtrsim 24$ μm. An even stronger bound arises if we require that the coupling λ is perturbative up to the Planck scale. In this case the renormalization group analysis gives that $\lambda \lesssim 0.76$ at the scale m_D, so that we obtain $l \gtrsim 110$ μm. These distance scales are within striking range of experiments searching for deviations from Newtonian gravity at sub-millimeter distances [13]. For a review of the current and future experimental status, and for alternative theories which also predict deviations from Newtonian gravity at sub-millimeter distances, see [14].

A similar signature can be obtained in the model of section 2.2 through the coupling of the S field to the standard-model gauge fields (Eq. (14) with Φ replaced by S – operators linear in Φ or $\bar{\Phi}$ are forbidden by the gauge symmetry). In this case l is determined by the mass of the scalar s: $l \simeq m_s^{-1}$, which does not have a solid bound as in the previous case. However, the naturalness of the model implies that radiative corrections to m_ϕ and $m_{\bar{\phi}}$ from m_s cannot be much larger than the values of m_ϕ and $m_{\bar{\phi}}$ themselves, which gives the bound $l \gtrsim (\lambda/4\pi)\sqrt{\ln(M_*/\Lambda)}\, m_{\bar{\phi}}^{-1}$. For $\lambda \simeq 10^{-3}$, this gives $l \gtrsim 2$ μm. Moreover, in the case that all the supersymmetry-breaking masses are the same order, i.e. $m_s \sim m_\phi, m_{\bar{\phi}}$, we obtain much tighter bound $l \gtrsim 3$ mm. The strength of the modification, α, can be of order 1 but, if the S field is responsible for the suppression of λ in Eq. (7), it could be of order $\lambda^2 \simeq 10^{-6}$.

Another possible signature of our models arises from the radiation energy density in the acceleressence sector, which we call dark radiation. This is especially interesting in the model of

section 2.2 because the acceleressence sector necessarily has a finite temperature. In particular, if the bound on Eq. (11) is nearly saturated, which is the case if λ is not much smaller than $10^{-3}g^2$, the radiation energy density ρ_ϕ is close to the upper bound allowed by nucleosynthesis, implying that this dark radiation will be seen in future cosmic microwave background experiments such as PLANCK or CMB-Pol. The signature from the dark radiation could also arise in the model of section 2.1 if the temperature of the acceleressence sector is not much lower than the value allowed by the big-bang nucleosynthesis constraint.

Finally, we note that the equation of state for acceleressence is essentially $w = -1$, except perhaps in the very recent past. Furthermore, superpartners must be discovered at the LHC with a spectrum that reflects a low mediation scale for supersymmetry breaking. If either of these proves to be incorrect, acceleressence dark energy will be excluded, at least in its minimal form as described in this paper.

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